Black hole unitarity via small couplings: basic postulates to soft quantum structure

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1701.08765, + preceding papers

BH unitarity problem:

A key problem expected to be a guide to the principles of quantum gravity

Our analog of H atom $\longleftrightarrow$ Discovery of QM   ?

Reveals an inconsistency in the principles underlying our best-tested framework for physics: LQFT

1) Relativity   2) QM   3) Locality

Indicates: new principles needed

How to find them?

Grand hope of string theory, loop quantum gravity…

(but also significant disappointments)

this talk will remain agnostic

Instead:

Use the need for a consistent description of BHs as guidance

What can we say based on some general, "plausible," physical principles?

Proposed principles:

Postulate I, *Quantum mechanics*: linear space of states, unitary S-matrix (in appropriate circumstances) …

Postulate II, *Subsystems*: The Universe can be divided into distinct quantum subsystems, at least to a good approximation

- weak version of locality of LQFT

- BH context: e.g. BH + its environment

- not trivial: in gravity, interesting and significant questions

see 1706.03104, w/ Donnelly

Postulate III, *Correspondence with LQFT*: Observations of small freely falling observers in weak curvature regimes are approximately well described by a local quantum field theory lagrangian. They find "minimal" departure from relativistic LQFT.

Includes observers crossing big horizons.

("nonviolent")

Postulate IV, *Universality*: Departures from the usual LQFT description influence matter and gauge fields in a universal fashion.

- optional ?

- well motivated: BH thermo; Gedanken experiments

III + IV ~ "Weak quantum equivalence principle"

Plan: follow these to logical conclusions.

If the conclusions are wrong, either:

One or more of these Postulates wrong: *interesting.*

Logic wrong. Also interesting?

If right, also interesting, as will see.

Comment on approach: working *towards* fundamental framework, don't have complete story

"Effective" description — parameterize departures from current best-tested framework, LQFT

Some questions premature.

Another way to describe:
Physical approach, based on *validity of QM*

Think of BH as another complex quantum subsystem,
like a complicated atom, or nucleus
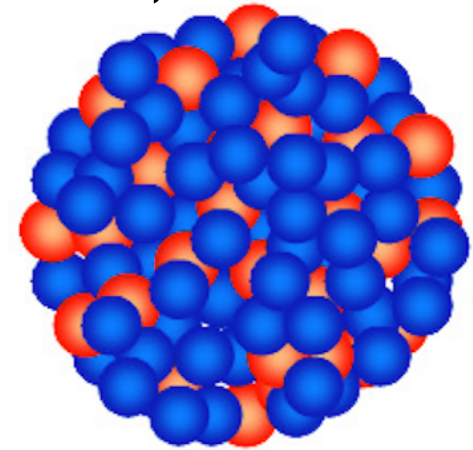
Parameterize its interactions with its environment

Try to reconcile:

1) need for information transfer out, for unitarity

2) ~appearance of vacuum BH, for infalling observers

This is very *conservative*:

Preserves QM

Match to QFT, minimal damage to its predictions
("Correspondence principle")

This is very *radical:*

Information escape apparently contradicts *locality,*
with respect to the semiclassical picture of a BH
violating a cornerstone principle of QFT

But, apparently *required* by *unitarity*

Hopefully right proportion of radical/conservative (*c.f.* Kuhn)

Warm up, Schrodinger picture evolution, LQFT in BH background

(also helpful in connecting w/ QI theory)

BH

horizon

r=0

R_n

v

r
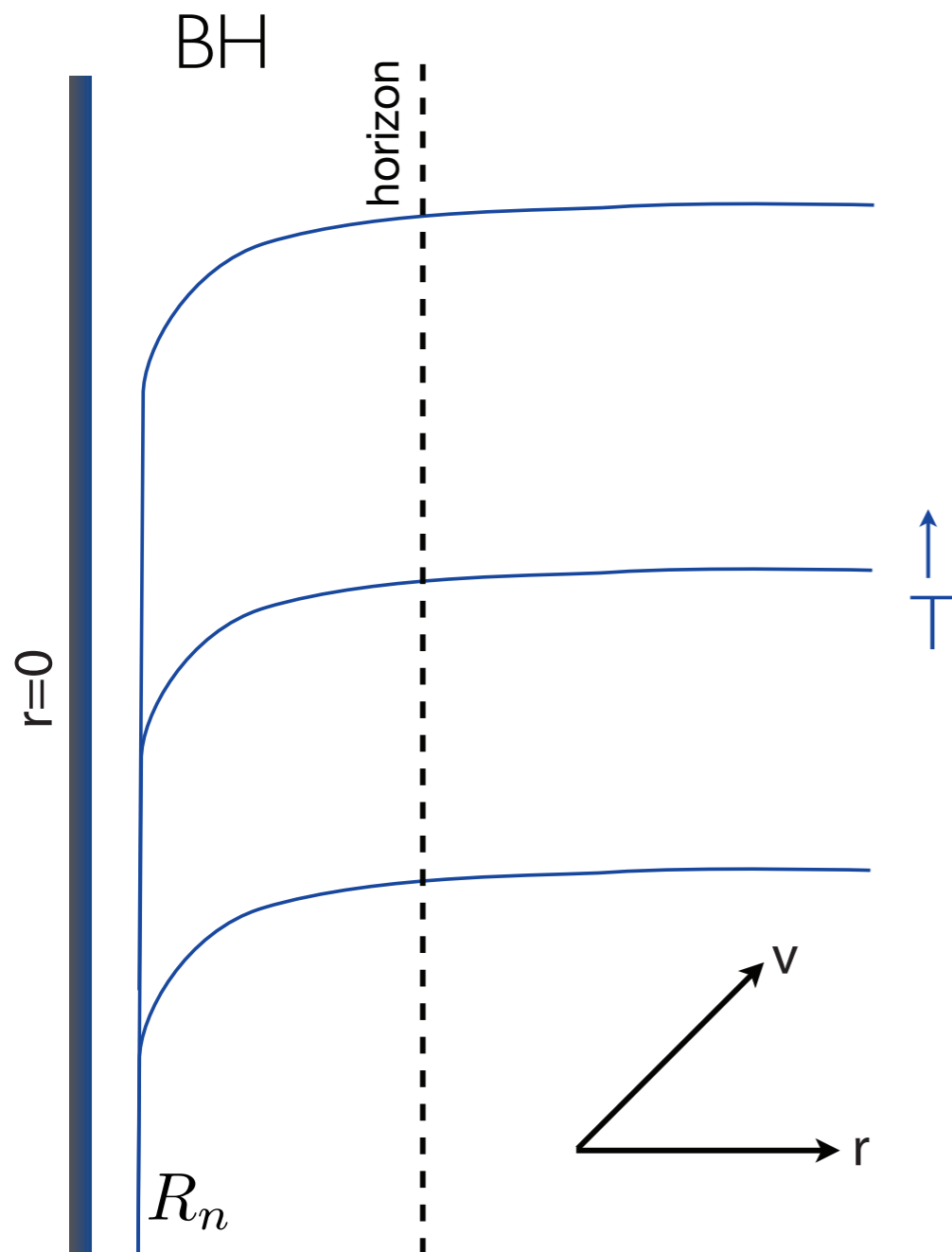
$$ds^2 = -N^2 dT^2 + q_{ij}(dx^i + N^i dT)(dx^j + N^j dT)$$

Evolution of scalar matter:

$$U = \exp\left\{ -i \int dT H(T) \right\}$$

T

$$H(T) = \int d^{D-1}x \sqrt{q} \left[\frac{1}{2} N(\pi^2 + q^{ij}\partial_i\phi\partial_j\phi) + N^i\pi\partial_i\phi \right]$$
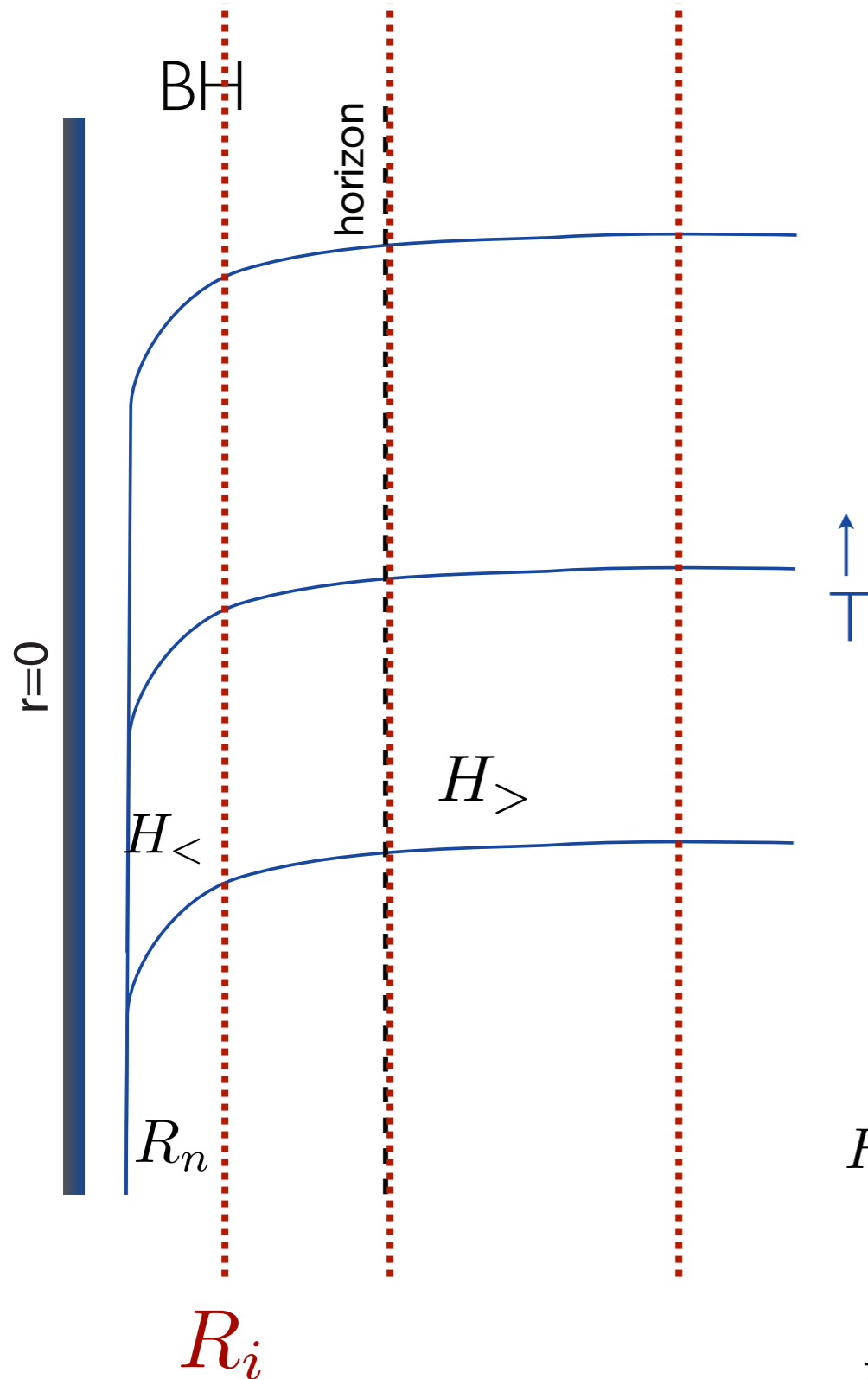
$$\pi(x) = -i\frac{\delta}{\delta\phi(x)}$$

(Unitary on these slices/G=0)

QM ✔

Subsystems:

In LQFT, subregions $\longleftrightarrow$ subalgebras subsystems

Subtlety in gravity: dressing

Small? $\qquad \sim \dfrac{GE_{cm}}{r}$

[SBG and Lippert;

Donnelly and SBG, 1507.07921]

Assume: good approx.

further development: w/ W. Donnelly, S. Weinberg

BH

horizon

r=0

$H_<$

$H_>$

R_n

R_i

$\uparrow$
$\top$

Evolution:

$$H = H_< + H_> + H_i$$

$$H_{\substack{< \\ >}} = \int_{\substack{r \leq R_i \\ >}} d^{D-1}x\sqrt{q}\left[\frac{1}{2}N(\pi^2 + q^{ij}\partial_i\phi\partial_j\phi) + N^i\pi\partial_i\phi\right]$$

H_i : local at R_i

The problem w/ this picture:

Unitarity ultimately fails (violates Postulate I)   G$\neq$0

Why?

1) H only increases entanglement with BH subsystem

Transfers info in, and Hawking radiation

2) BH subsystem has unbounded dimension

When BH disappears, unitarity violated

So, *modifications needed to save QM ("unitarize")*

Unitarization and soft quantum structure:

Structural modifications needed — follow postulates

Postulates I,II:

1) Interactions must transfer information (entanglement) out

$$H_I \qquad\qquad \sim 1 \text{ qubit/R}$$

2) Internal Hilbert space must behave finite-dimensionally

$$K = 1, \cdots, N \sim e^{S_{bh}} \quad \text{in} \quad \Delta M \sim 1/R$$

$$|K, M; \psi_e, T\rangle$$

$$H_I$$

Structure of H_I ?   Postulate III: ~LQFT, $r > R_i$

Bilinear needed to transfer information:

$$H_I = \sum_{Ab} \int d^{D-1}x \sqrt{q}\, G_{Ab}(x)\, \lambda^A\, O^b(x)$$

U(N) generators   Act on > subsystem

$G_{Ab}(x)$:   parameterize ignorance

"Quantum structure"

Constraints: 1) "Minimize" departure from LQFT

- Supported near the BH   Scale R_a

- Not restricted too near the BH

$R_a = R + l_{pl}$: "FW" $R_a \sim R$: nonviolent

(tuned)

- Only connect states w/, e.g., $\Delta M \sim 1/R$

2) Need sufficient information transfer   ~1/R

Focus on example: from Postulate IV - universal couplings

Can generalize this, but well motivated:

1) mining Gedanken exps   2) ~match BH thermo

$$H_I = \int d^{D-1}x \sqrt{q} \underbrace{\sum_A \lambda^A G_A^{\mu\nu}(x)}_{H^{\mu\nu}(x)} T_{\mu\nu}(x)$$

"BH state-dependent metric perturbation"

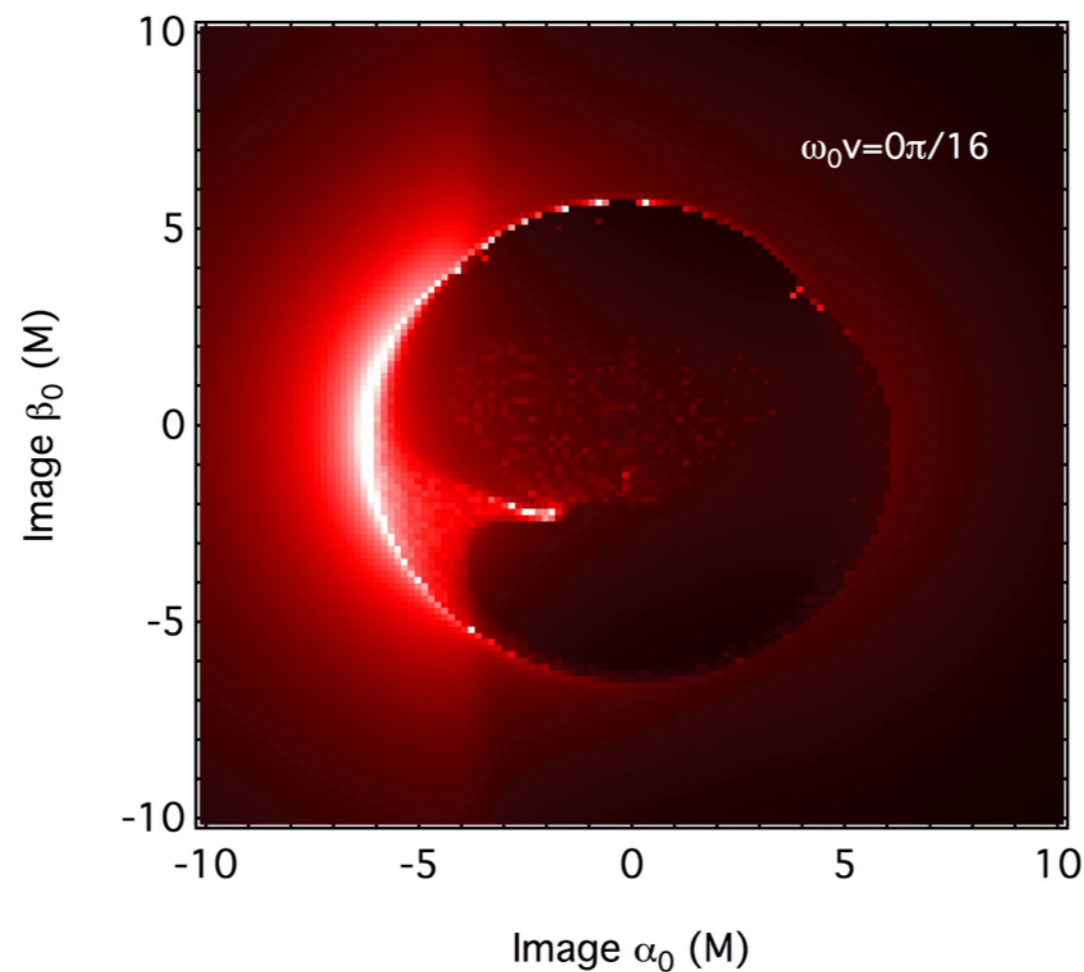Sufficient transfer: $\langle \psi, T | H^{\mu\nu}(x) | \psi, T \rangle \sim 1$

arXiv:1401.5804   fluctuation scales ~ R

This could produce observable effects, e.g. via Event Horizon Telescope! (Sgr A*, M87)

$$\langle \psi, T | H^{\mu\nu}(x) | \psi, T \rangle \sim 1$$

[SG/Psaltis]

1606.07814

But, are such large effects *necessary*?

$$H_I = \int d^{D-1}x \sqrt{q} \sum_A \lambda^A G_A^{\mu\nu}(x) \, T_{\mu\nu}(x)$$

Reorganize:

Expand: $G_A^{\mu\nu}(x) = \sum_{\gamma=1}^{\chi} c_{A\gamma} f_\gamma^{\mu\nu}(x)$ Small basis of tensor functions

(Postulate III-NV)

$$O_\gamma = \sum_A \lambda^A c_{A\gamma} \qquad\qquad T_\gamma = \int d^{D-1}x \sqrt{q} f_\gamma^{\mu\nu}(x) T_{\mu\nu}(x)$$

$$\boxed{H_I = \sum_{\gamma=1}^{\chi} O_\gamma T_\gamma}$$
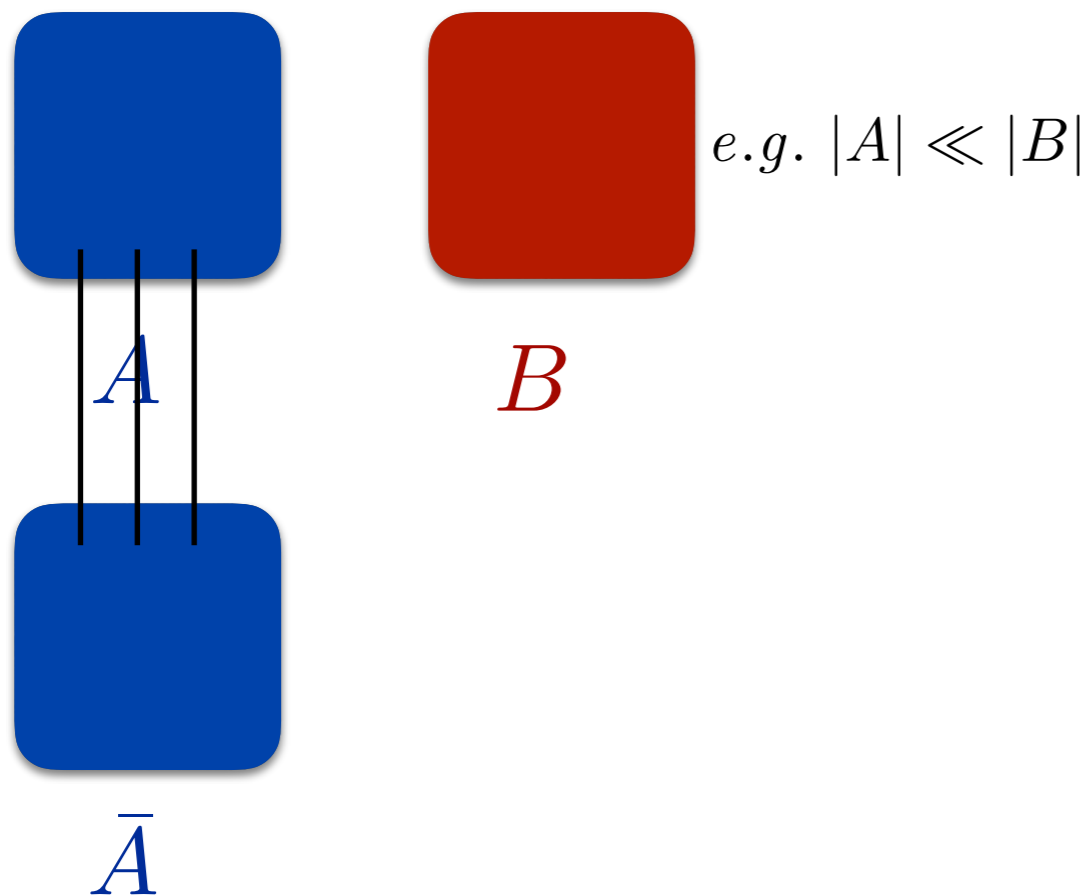
χ "channels"

What size couplings, for necessary transfer of information?

How fast does information transfer, given such couplings?

A problem (unsolved?) and conjecture in quantum information theory

Subsystems

A

$\bar{A}$

B

$e.g.\ |A| \ll |B|$

$$H = H_A + H_B + H_I$$

$$H_I = \mathcal{E} \sum_{\gamma=1}^{\chi} c_\gamma O_A^\gamma O_B^\gamma$$

Sets scale

$$\|O_{A,B}^\gamma\| = 1$$

How fast transfers information?

$$I(\bar{A} : B) = S_{\bar{A}} + S_B - S_{\bar{A}B}$$

Take, e.g., $\quad H_A = \mathcal{E} \sum_a h_a \lambda^a \qquad$ likewise for B.

$$\sum_a (h_a)^2 / |A| = 1$$

~"random"

Conjecture:

$$\frac{dI}{dt} = C\mathcal{E} \sum_{\gamma=1}^{\chi} c_\gamma^2 \qquad \text{for small} \quad c_\gamma$$

(… now under investigation w/ Rota and Nayak)

Apply to BHs:

$$H_I = \sum_{\gamma=1}^{\chi} O_\gamma T_\gamma$$

$$O_\gamma = \sum_A \lambda^A c_{A\gamma}$$

$$T_\gamma = \int d^{D-1}x \sqrt{q} f_\gamma^{\mu\nu}(x) T_{\mu\nu}(x)$$

Normalize: $\quad \|T_\gamma\| = \mathcal{E} \sim \dfrac{1}{R}$

Conjecture implies:

$$\frac{dI}{dt} = C\mathcal{E} \sum_\gamma \|O_\gamma\|^2$$

$$\sim \frac{1}{R}$$

for $\displaystyle\sum_{\gamma=1}^{\chi} \|O_\gamma\|^2 \sim 1 \quad \longleftrightarrow \quad \sum_{A\gamma} c_{A\gamma}^2 \sim N \quad \longleftrightarrow \quad$

$$c_{A\gamma} \sim \sqrt{1/N\chi}$$
$$\sim e^{-S_{bh}/2}$$

One motivation: Fermi's Golden Rule

$$H_I = \sum_{\gamma=1}^{\chi} O_\gamma T_\gamma$$

$|\psi\rangle \to |K\rangle$ BH transitions:

$$\Gamma \approx 2\pi \omega^{bh}(E) \sum_\gamma |\langle K|O_\gamma|\psi\rangle|^2 \; |\langle \beta|T_\gamma|\alpha\rangle|^2$$

$$\sim \frac{1}{R} : \quad \langle K|O_\gamma|\psi\rangle \sim 1/\sqrt{N\chi} \sim e^{-S_{bh}/2}$$

So tiny couplings apparently suffice

(Many states contribute)

contrary to previous arguments

This also means, by similar scaling:

$$\langle \psi, T | H^{\mu\nu}(x) | \psi, T \rangle \sim \frac{1}{\sqrt{N}} \sim e^{-S_{bh}/2}$$

Tiny!

Another way to think of:

incoherent effect $\langle \psi | H_{\mu\nu} | \psi \rangle \sim e^{-S_{bh}/2}$

vs.

coherent effect $\langle \psi | H_{\mu\nu} | \psi \rangle \sim 1$

But estimate effect on matter near BH: Fermi's rule

$$\Gamma \approx 2\pi\omega^{bh}(E) \sum_{\gamma} |\langle K|O_\gamma|\psi\rangle|^2 \; |\langle\beta|T_\gamma|\alpha\rangle|^2$$

where $\quad \alpha, \; \beta \quad$ are states of scattered matter

- also can be $\quad \mathcal{O}(1/R)$

- expected $\quad \Delta p \sim (1/R) \quad$ ("nonviolence")

- tiny effect on matter

- but: possible signal in GWs?

So, to summarize,

Unitarization possible with

$$\langle \psi, T | H^{\mu\nu}(x) | \psi, T \rangle \sim 1$$

potentially observable effects (EHT, GWs)

But present arguments also say possible with

$$\langle \psi, T | H^{\mu\nu}(x) | \psi, T \rangle \sim \frac{1}{\sqrt{N}} \sim e^{-S_{bh}/2}$$

small effect on matter; possible impact on GWs

Future questions

Improved understanding of such "entropy-enhanced" transfer

- Refinement/proof of conjecture   [SBG,Nayak, Rota, WIP]

- Size of exterior effects - GWs, etc.: more systematic

Observability

Event Horizon Telescope?

LIGO?

Important *empirical* question

Current BH stories: *new physics* at ~R

More complete description

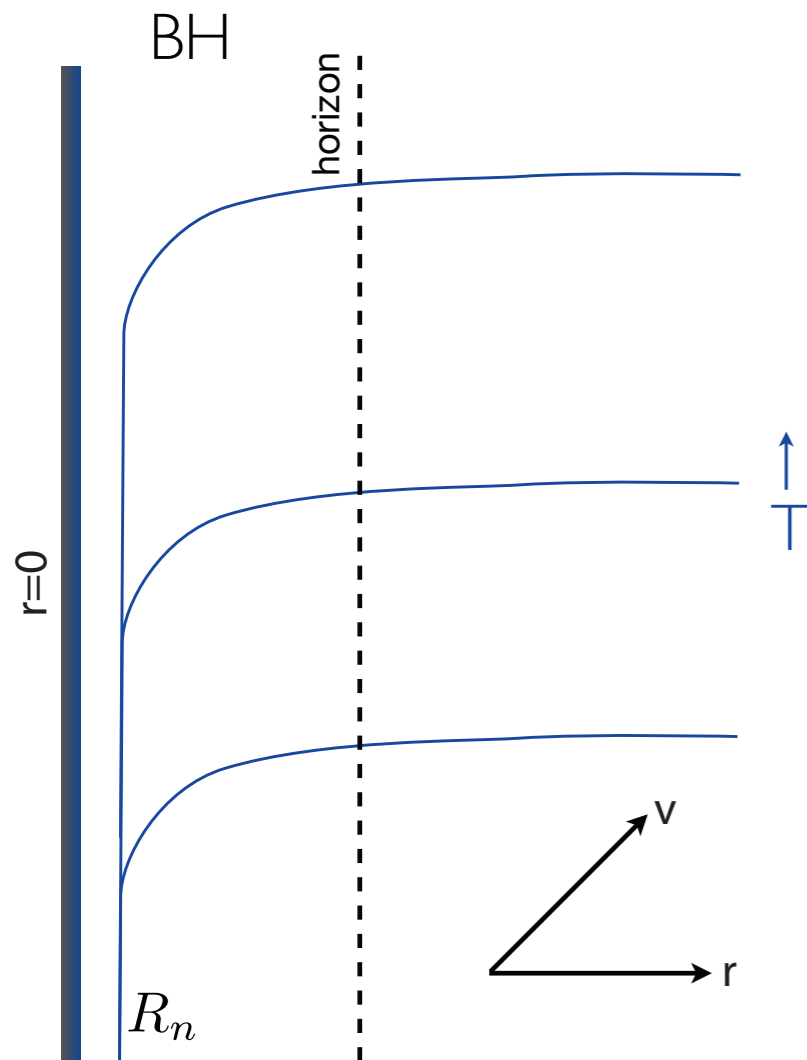Connection w/ subsystem subtleties/dressing
maybe soft quantum hair?

though, 1706.03104 w/ Donnelly, +WIP…

More complete thermodynamic tests

Foundational picture for QG, respecting principles

Backups

BH slicing: explicit description

$$ds^2 = -f(r)dv^2 + 2dvdr + r^2d\Omega_{D-2}^2$$

$$f(r) = 1 - \mu(r)$$

$$\mu(r) = \left(\frac{R}{r}\right)^{D-3}$$

$$v = T + s(r)$$

arbitrary; e.g. $s(r) = r$

$$ds^2 = -N^2dT^2 + q_{ij}(dx^i + N^idT)(dx^j + N^jdT)$$

$$N^2 = \frac{1}{s'(2 - fs')} \quad , \quad N_r = 1 - fs' \quad , \quad q_{rr} = s'(2 - fs')$$

$s(r) = r:$ $\quad N^2 = \frac{1}{1 + \mu(r)} \quad , \quad N_r = \mu(r) \quad , \quad q_{rr} = 1 + \mu(r)$

How fast does information transfer, given these couplings?

Example of a general unsolved(?) problem in Q. info theory

(Work in progress w/ Nayak and Rota)

Conjecture: If normalize: $\|T_\gamma\| = \mathcal{E} \sim \dfrac{1}{R}$

$$\frac{dI}{dt} = C\mathcal{E} \sum_{\gamma, A} c_{A\gamma}^2 / N \qquad \left(H_I = \sum_{\gamma=1}^{\chi} \sum_A \lambda^A c_{A\gamma} T_\gamma \right)$$

(e.g. motivated by Fermi's Golden Rule)

$$\Rightarrow \qquad \frac{dI}{dt} \sim \frac{1}{R} \qquad \text{for} \qquad c_{A\gamma} \sim \sqrt{1/N} \sim e^{-S_{bh}/2}$$

"tiny interactions; many final states"